Spin Qubit Control using NV Centres in Diamond

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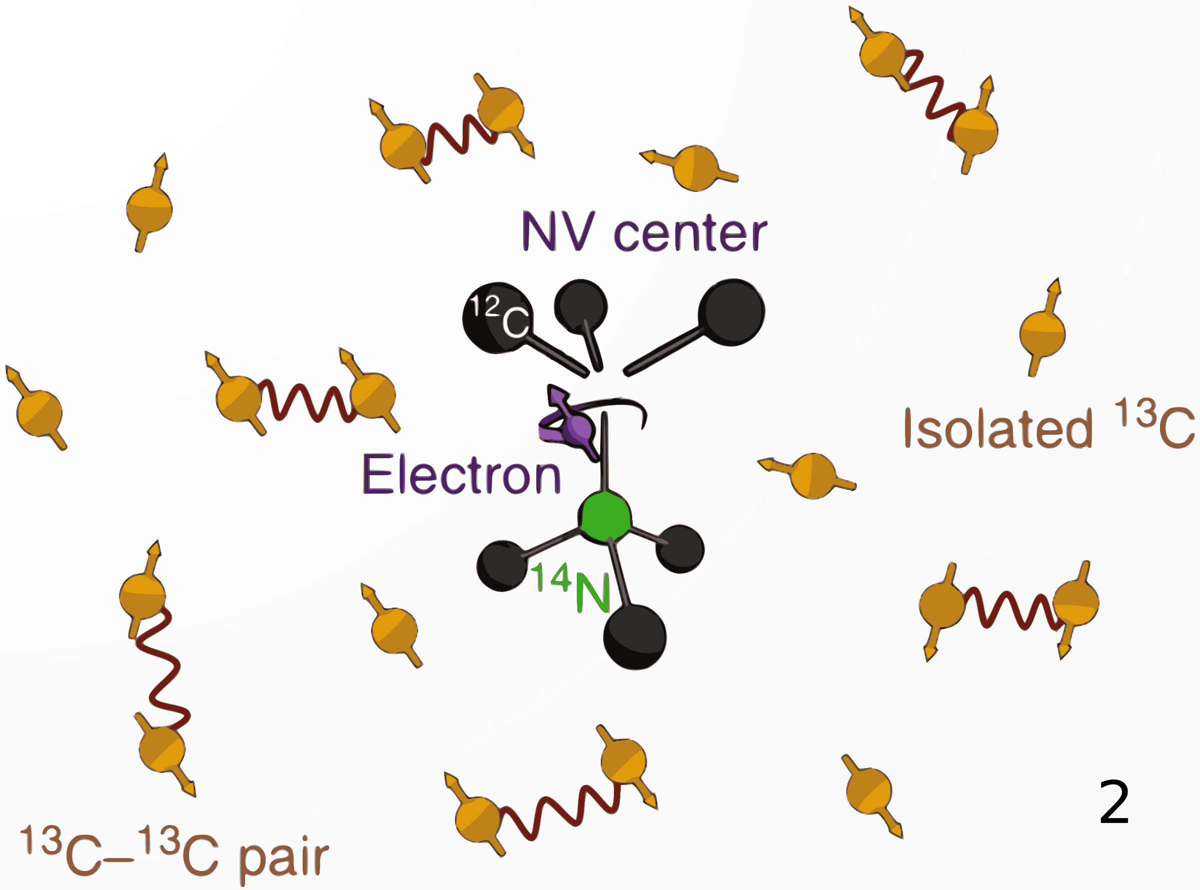
Outline

- NV Centres – defect centres in diamond which, along with surrounding $^{13}\mathrm{C}$, constitute promising platforms for effective qubits
- Model and simulation – implemented an error model to simulate decoherence
- Dynamical decoupling – with perfect and imperfect π-rotations to extend decoherence time for spin qubits

Nitrogen-Vacancy Centres

- NV centres are spin-1 defects in the crystal structure of diamond, effective 2-level system
- $^{12}\mathrm{C}$ bath protects spin of NV
- Surrounding $^{13}\mathrm{C}$ atoms (spin-1/2) can be used as storage qubits
- Main Challenge – mitigating decoherence through dephasing noise due to magnetic fluctuations from surrounding $^{13}\mathrm{C}$ spin bath[1]



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[1] van der Sar, T., Wang, Z., Blok, M. et al. Decoherence-protected quantum gates for a hybrid solid-state spin register. Nature 484, 82–86 (2012). https://doi.org/10.1038/nature10900

[2] Abobeih, M.H., Cramer, J., Bakker, M.A. et al. One-second coherence for a single electron spin coupled to a multi-qubit nuclear-spin environment. Nat Commun 9, 2552 (2018). https://doi.org/10.1038/s41467-018-04916-z

System Simulation

Evolution of state:

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho]$$

ρ Density matrix.

H Hamiltonian.

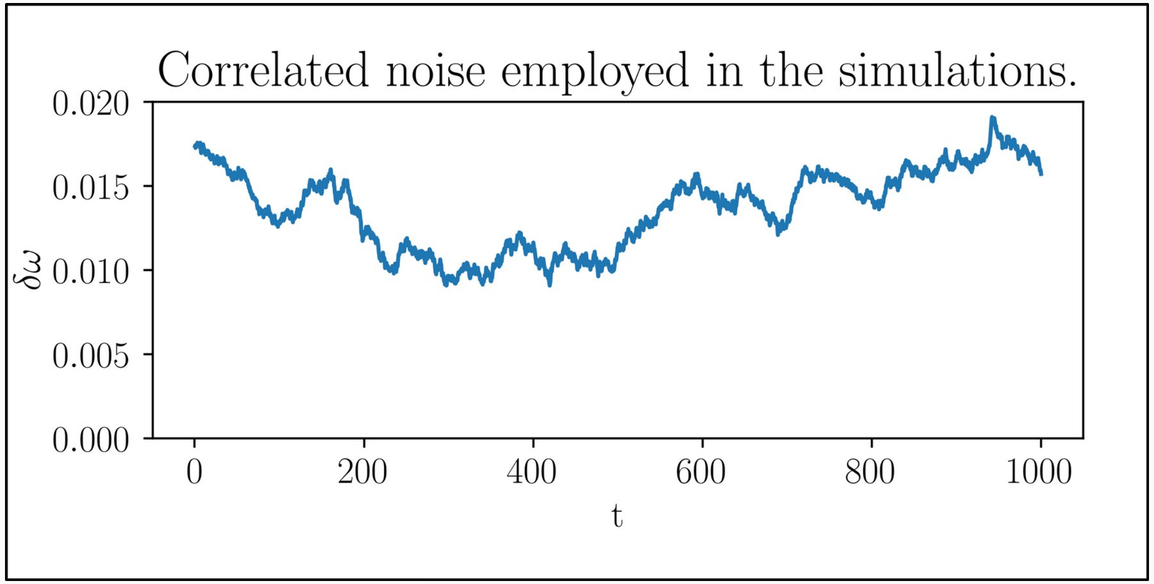
Numerical simulations performed with *Runge-Kutta 4*.

Error model:[‡]

$$H(t) = \delta\omega(t)\sigma_Z$$

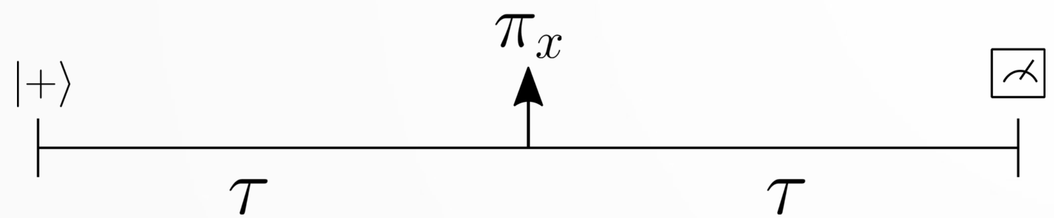
Autocorrelated normal noise (average final values 960 times),

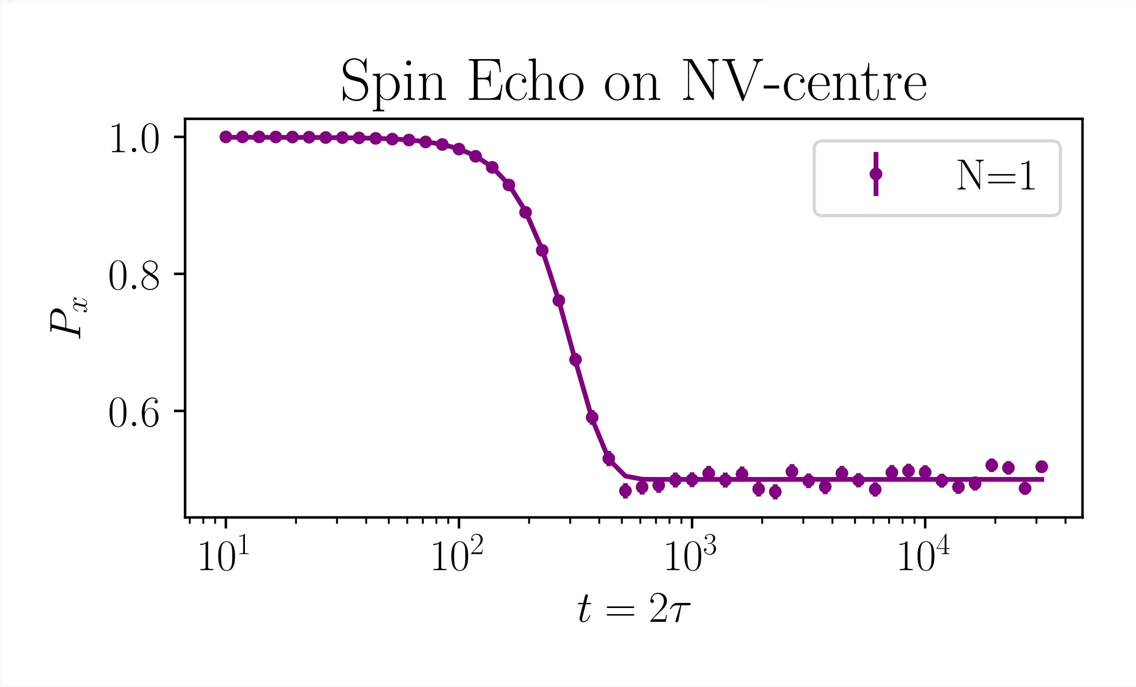
$$\langle \delta\omega(t)\delta\omega(0)\rangle = \sigma^2 e^{-t/\tau_c}$$



[‡] Wang, Zhi-Hui et al. "Comparison of Dynamical Decoupling Protocols for a Nitrogen-Vacancy Center in Diamond." Physical Review B 85.15 (2012): https://doi.org/10.1103/PhysRevB.85.155204

Spin echo





Simulation parameters:

$$\langle \delta\omega(t)\delta\omega(0)\rangle = b^2 e^{-|t|/\tau_c}$$

$$\tau_c = 10^5 \qquad b = 0.05$$

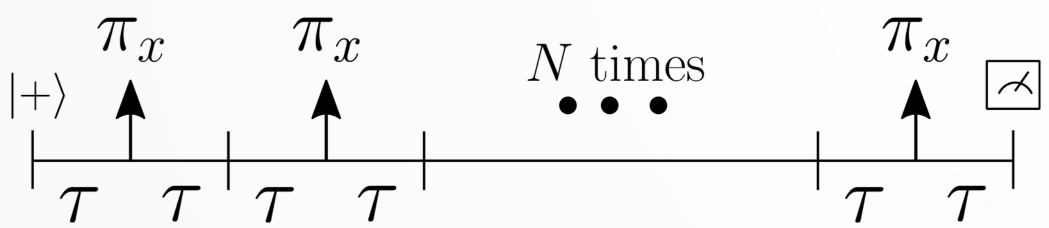
Fit function:

$$P_x = \frac{1 + e^{-(t/T_2)^n}}{2}$$

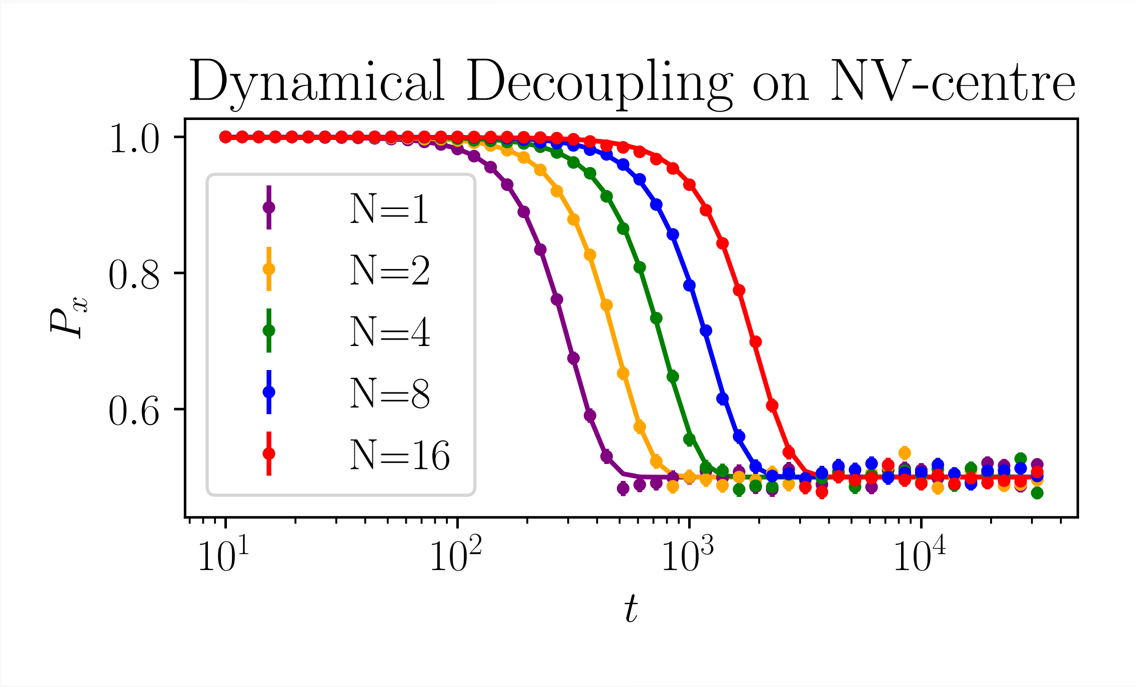
Theory: $\left\{ \begin{array}{l} T_2 = 782 \\ n = 3.0 \end{array} \right.$

Simulation: $\left\{ \begin{array}{l} T_2 = 310(3) \\ n = 3.0(1) \end{array} \right.$

Dynamical Decoupling



Same simulation parameters

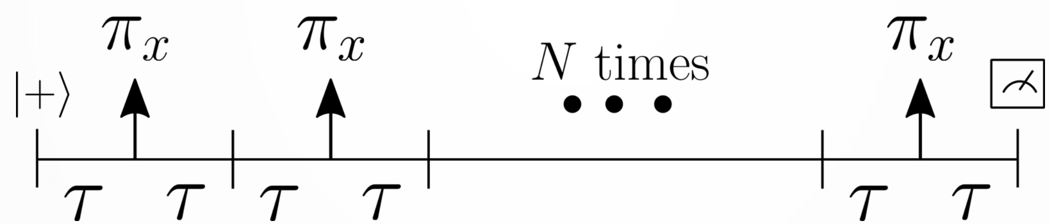


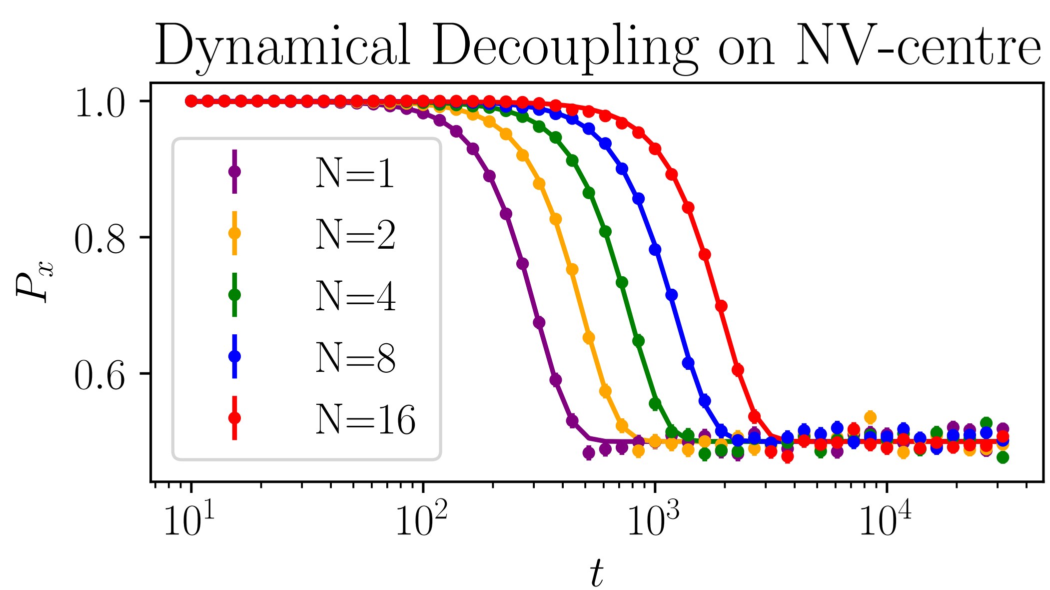
Same fit function: $P_x = \frac{1 + e^{-\left(t/T_{\frac{1}{e}}\right)^n}}{2}$

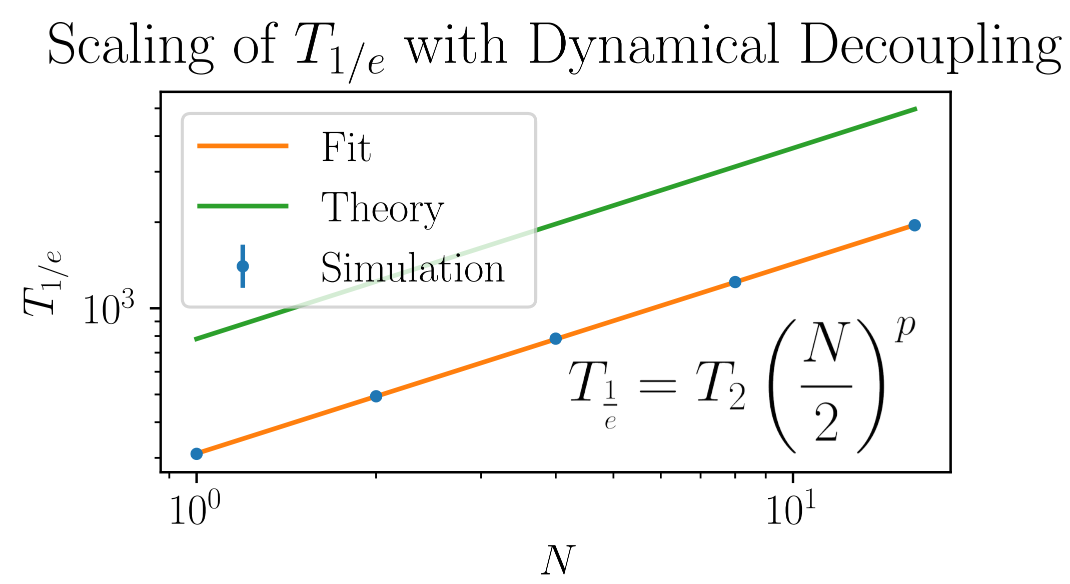
Theory: $n = 3.0$

Worst simulation: $n = 2.90(7)$

Dynamical Decoupling



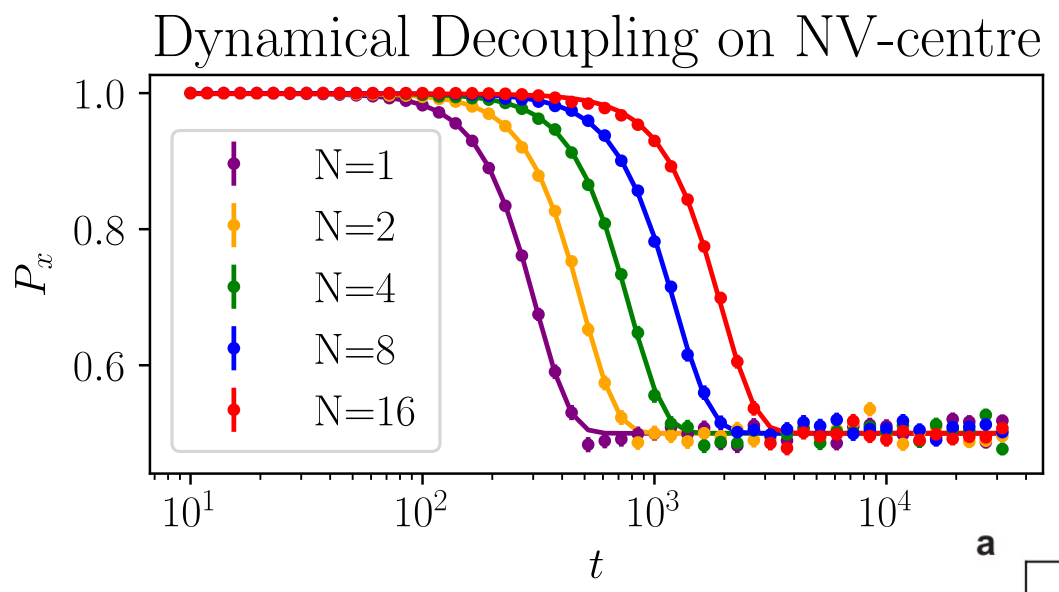




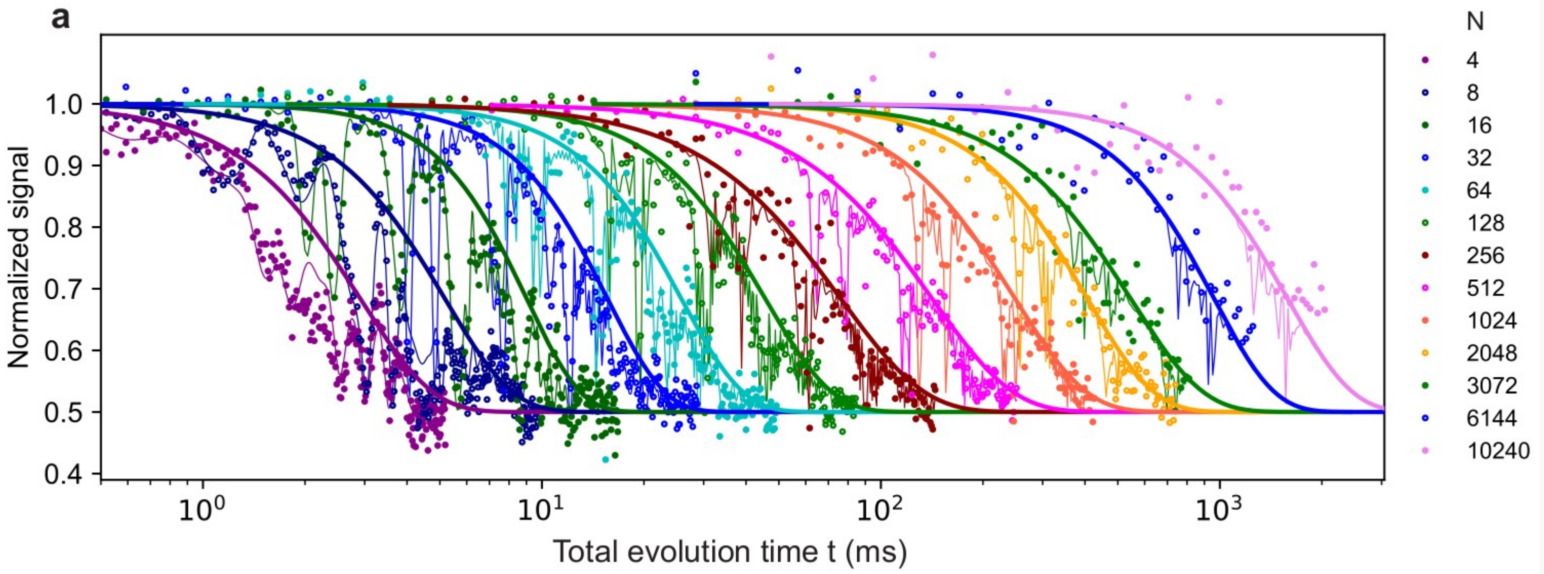
$$p_{\text{theory}} = 2/3$$

$$p_{\text{simulation}} = 0.663(1)$$

Dyn Decoupling



- Same qualitative features between simulation and experiment (envelope)
- Values of n for the fit vary from 1.8 to 2.8



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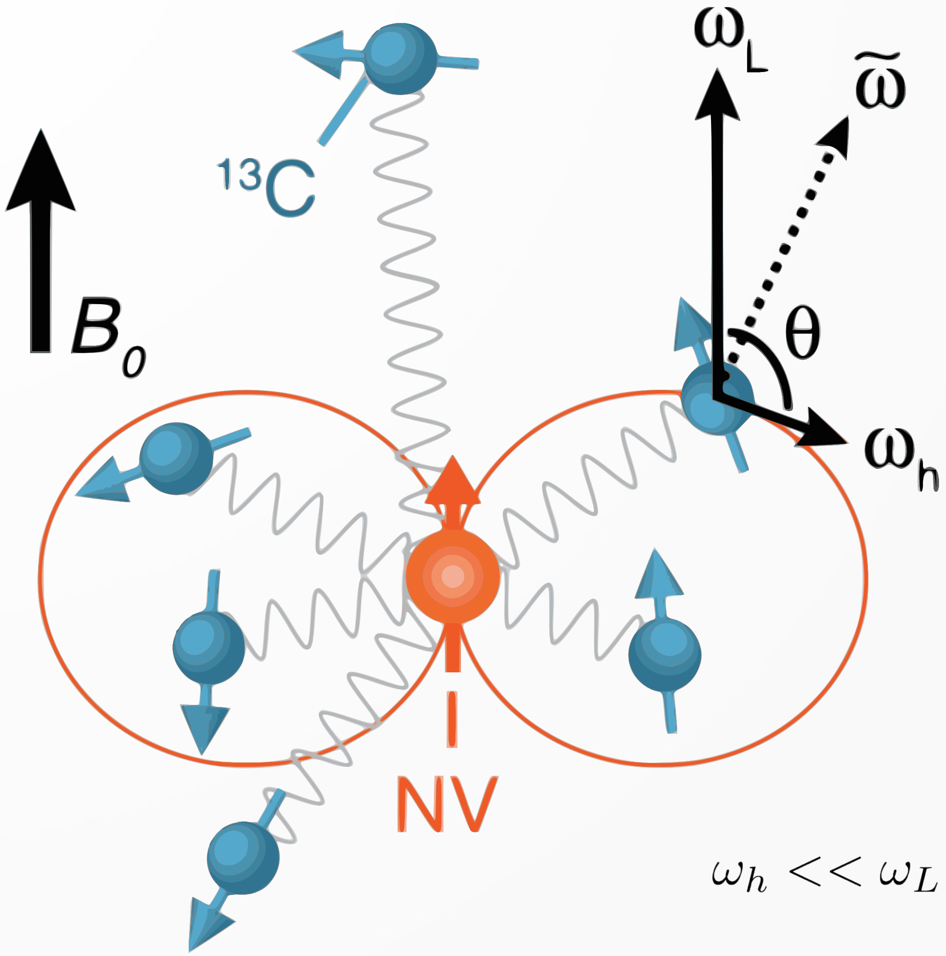
NV-Carbon Interaction

- Hamiltonian of the $^{13}\mathrm{C}$ atoms is dependent on the NV centre spin state

$$H_0 = \omega_L \hat{S}_z$$

$$H_1 = (\omega_L + w_h cos\theta)\ \hat{S}_z + w_h sin\theta\ \hat{S}_x$$

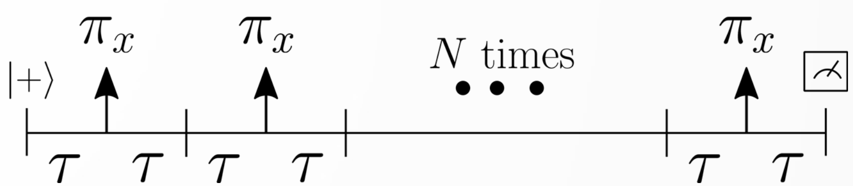
- Raises possibility of individual control because each $^{13}\mathrm{C}$ has its own resonance with the NV centre

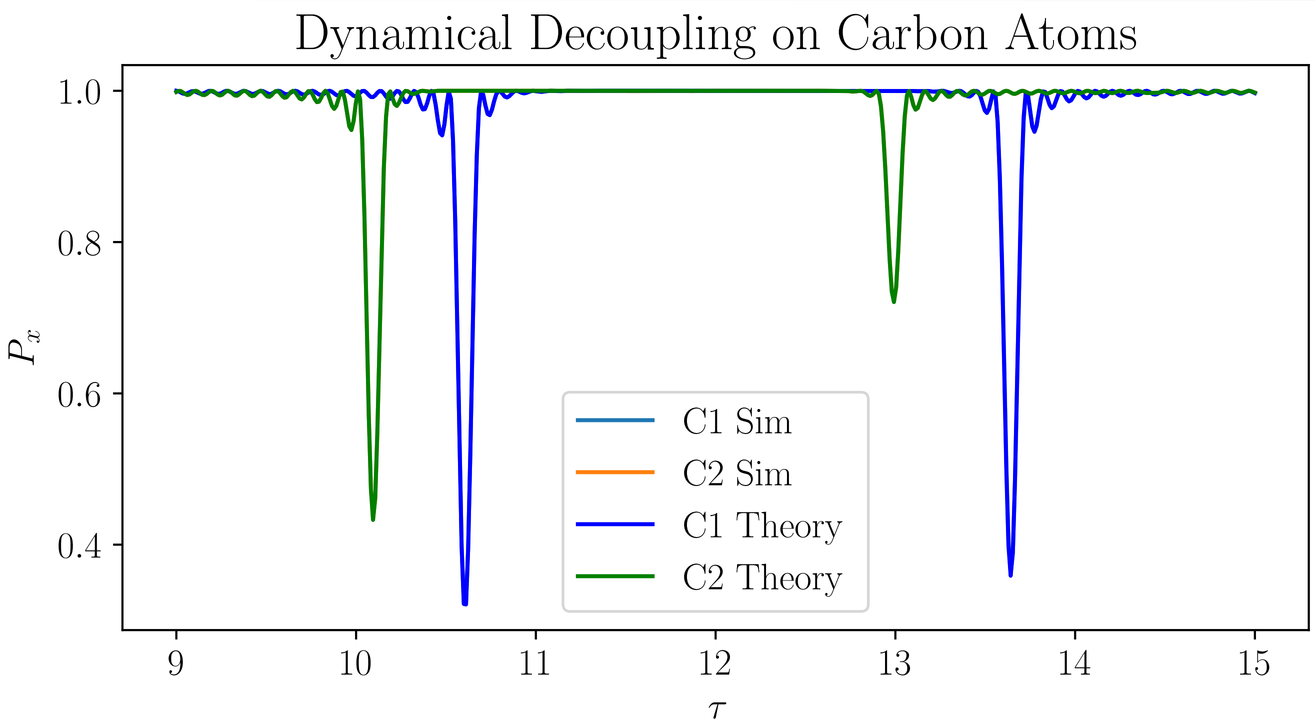


$\omega_h << \omega_L$

Dynamical Decoupling and Entanglement Generation

- Initialize NV in $|+\rangle$ and the $^{13}\mathrm{C}$ in the mixed state ρ_m
- Due to conditional interaction between NV and Carbon only at special resonant frequencies, entanglement appears as small peaks
- Simulation coincides perfectly with the theoretical prediction*

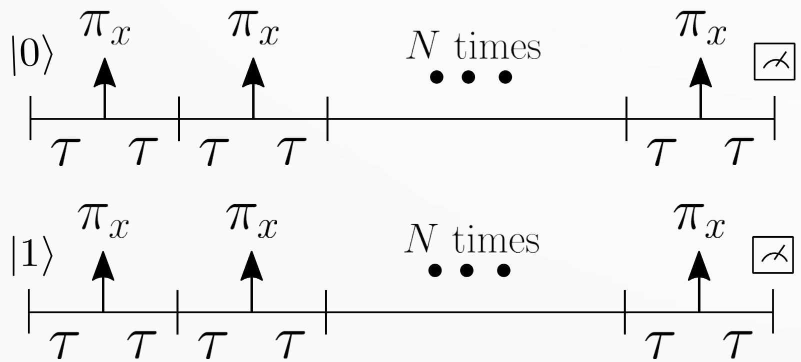


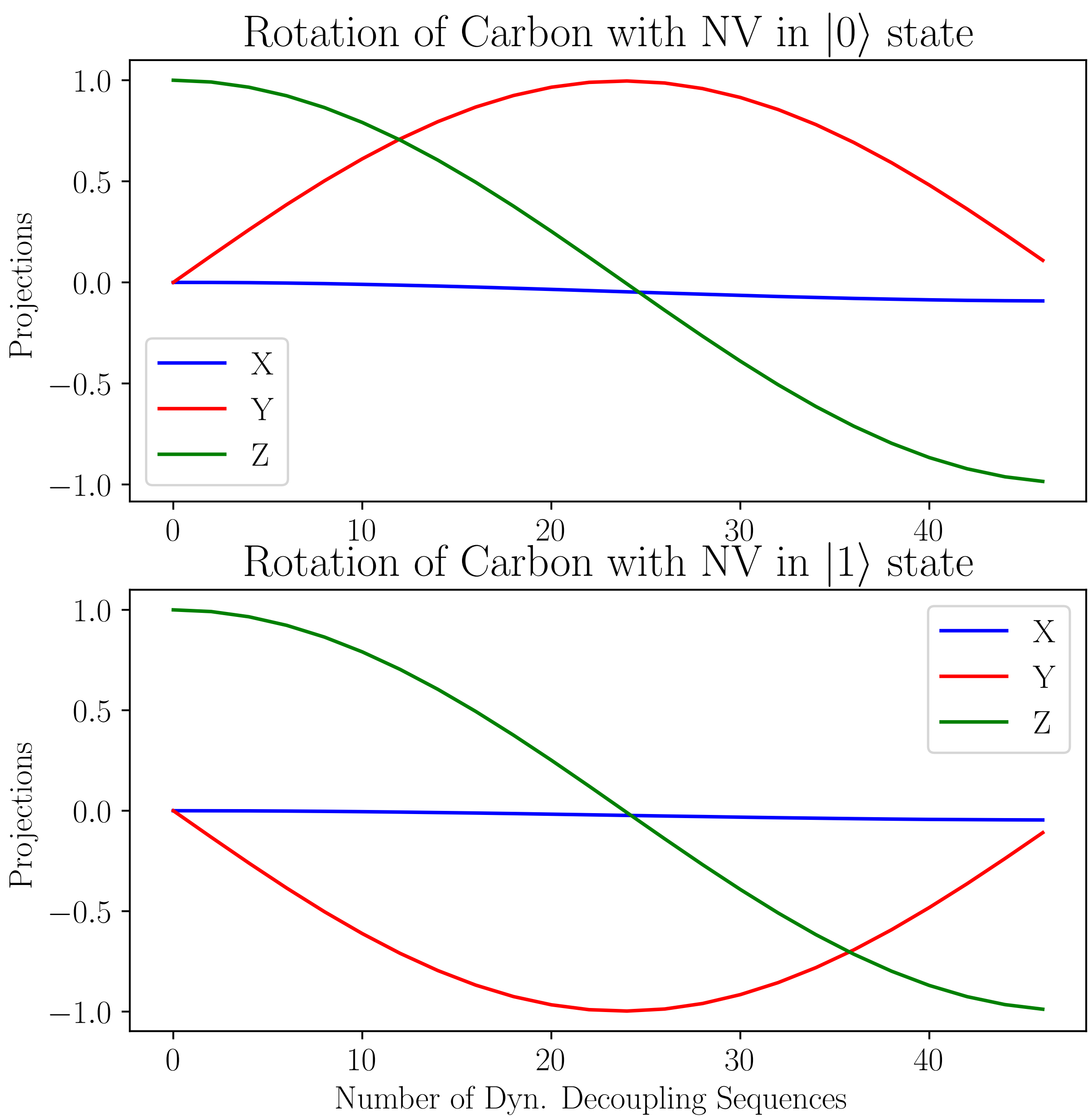


* Taminiau, T. H. et al. “Detection and Control of Individual Nuclear Spins Using a Weakly Coupled Electron Spin.” Physical Review Letters 109.13 (2012) https://doi.org/10.1103/PhysRevLett.109.137602

Controlled Rotation of Carbons

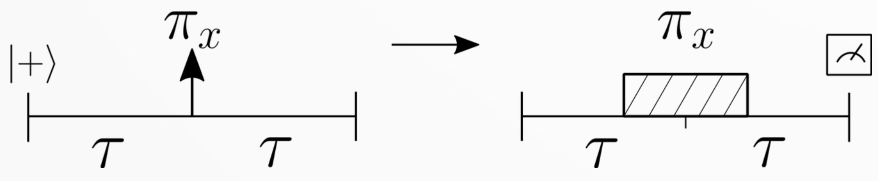
- By flipping the spin state of the NV centre at the resonant precession frequency for a $^{13}\mathrm{C}$, we can implement coherent rotations
- Direction of rotation is conditional on initial spin of the NV
- Even with just ~40 sequences, capable of performing π-rotation with over 99% fidelity



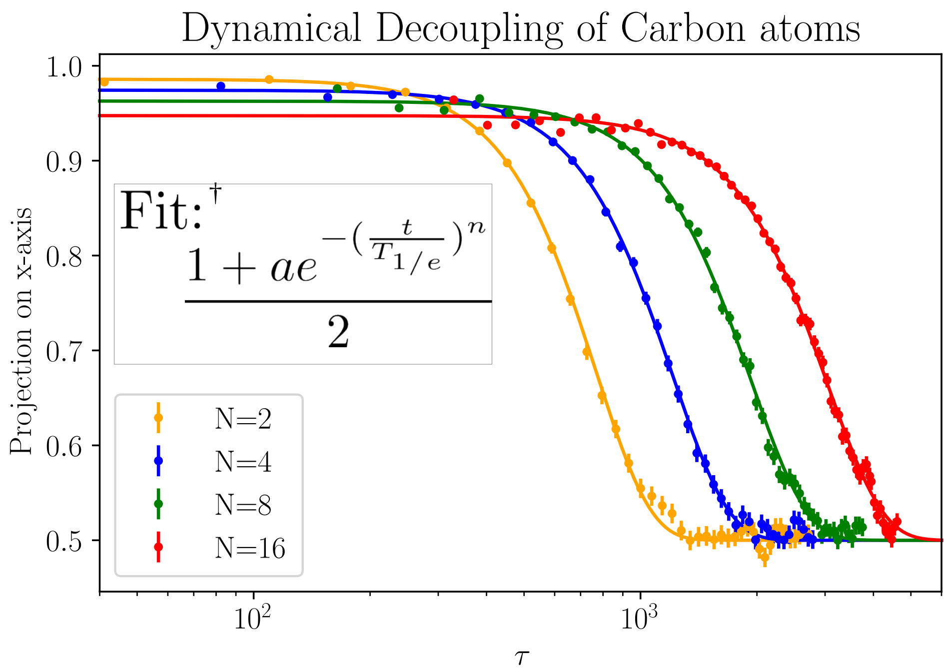


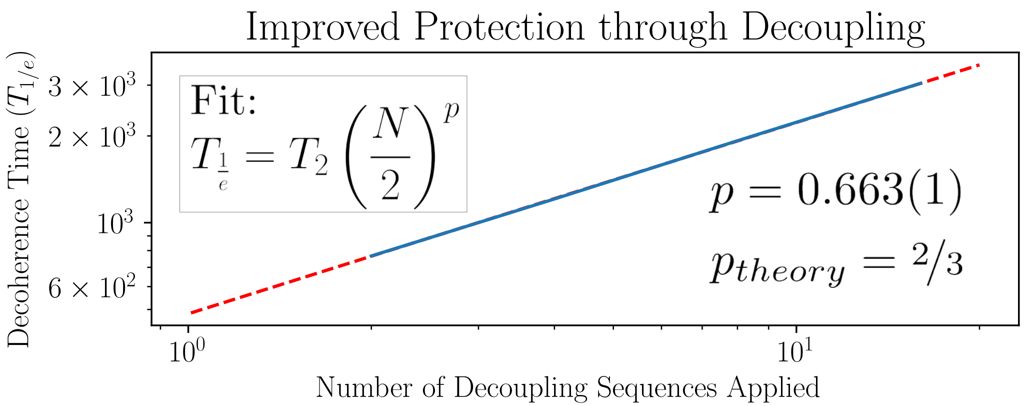
Dynamical Decoupling on Carbon

- To protect the $^{13}\mathrm{C}$ from dephasing noise, we can implement the spin-echo protocol similar to that on the NV
- Main Difference - cannot implement π-rotations directly, must be mediated by NV centre, and thus they take much longer



- More rotations lead to better protection (higher fidelity for longer time)





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Conclusion

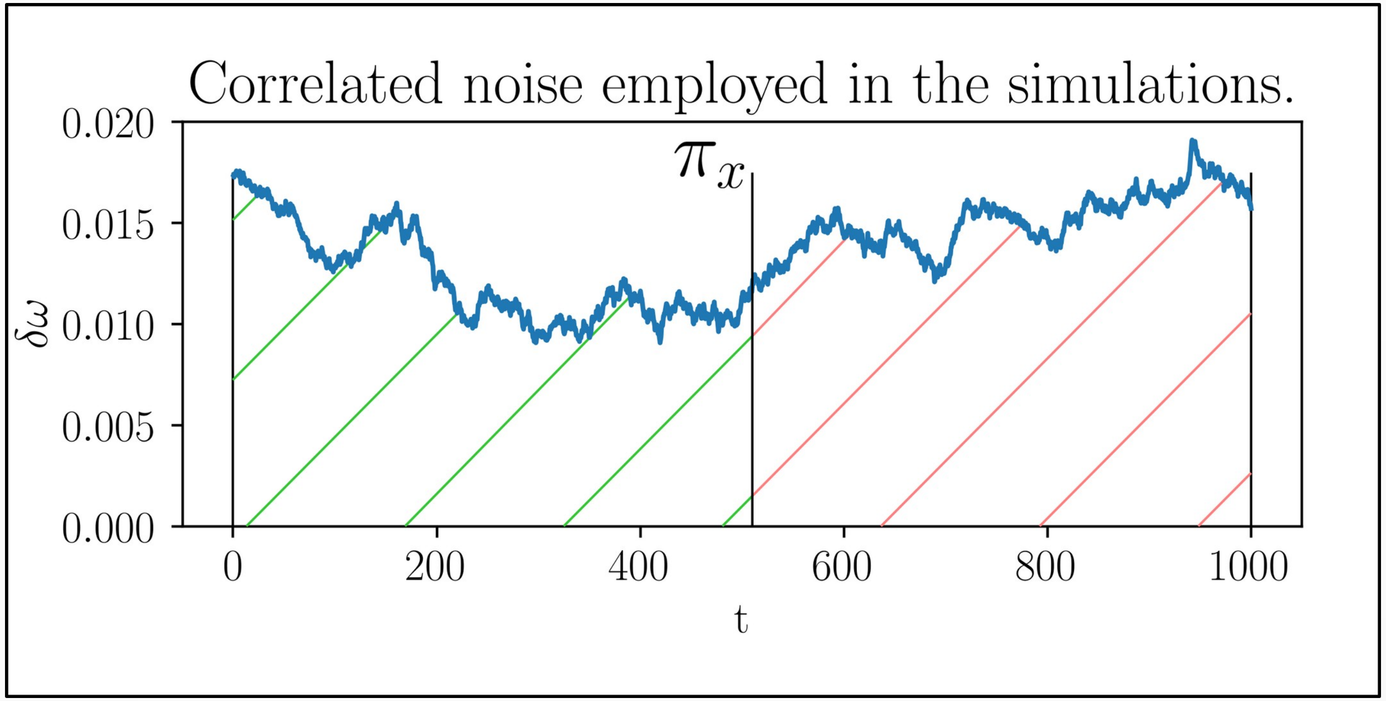
- Decoherence can be mitigated by to some extent using dynamical decoupling sequences, addressing a key challenge in the use of NV centres as nodes for quantum computing
- Our model qualitatively describes the system's evolution under decoupling sequences, obtaining the values for several parameters correctly
- Due to the way the simulation scales with time, simulating for high N values was not feasible. Performance could be improved by implementing time evolution directly rather than using the Lindblad equation
- Future Outlook – probing the effect of different types of decoupling sequences on the spin qubits, as done in recent papers[†]

[†] Wang, Zhi-Hui et al. "Comparison of Dynamical Decoupling Protocols for a Nitrogen-Vacancy Center in Diamond." Physical Review B 85.15 (2012): https://doi.org/10.1103/PhysRevB.85.155204

Thank you!

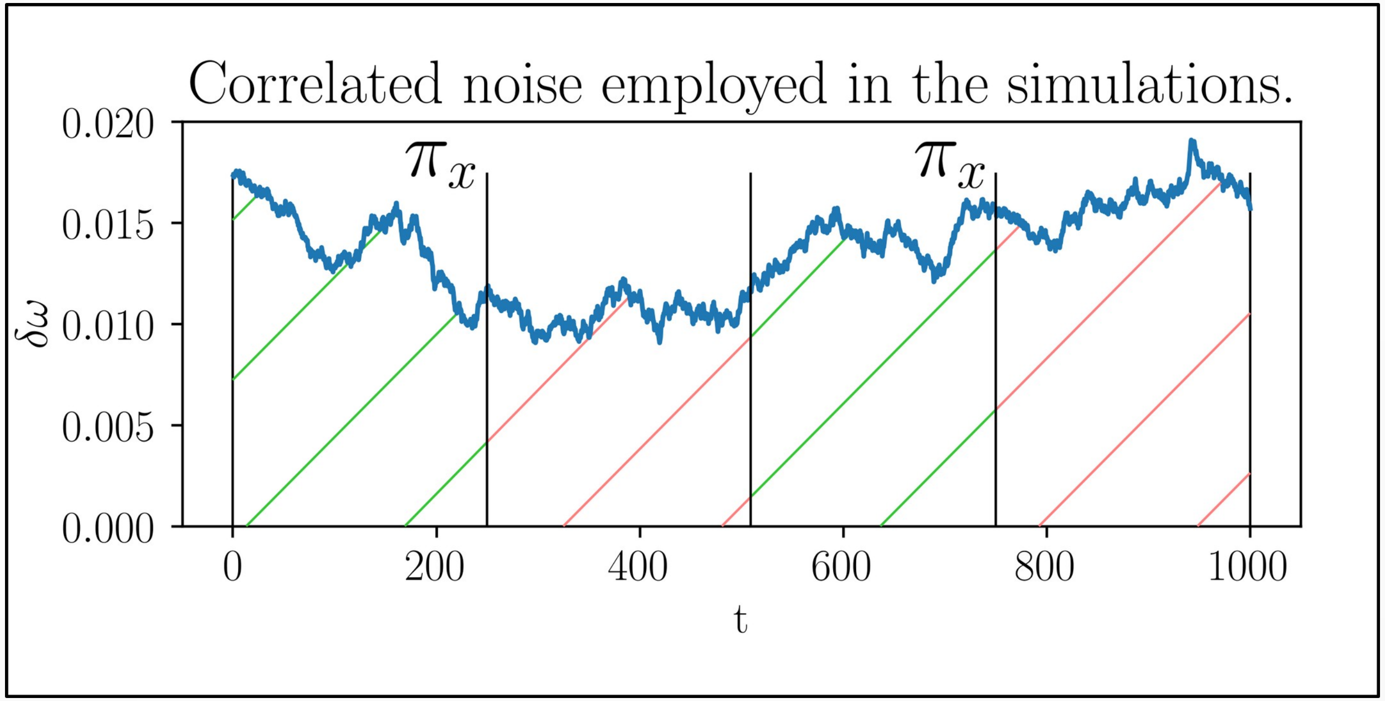
Questions?

Appendix



Correlated noise employed in the simulations.
π_x
$\delta\omega$
0.020
0.015
0.010
0.005
0.000
0
200
400
600
800
1000
t

Appendix



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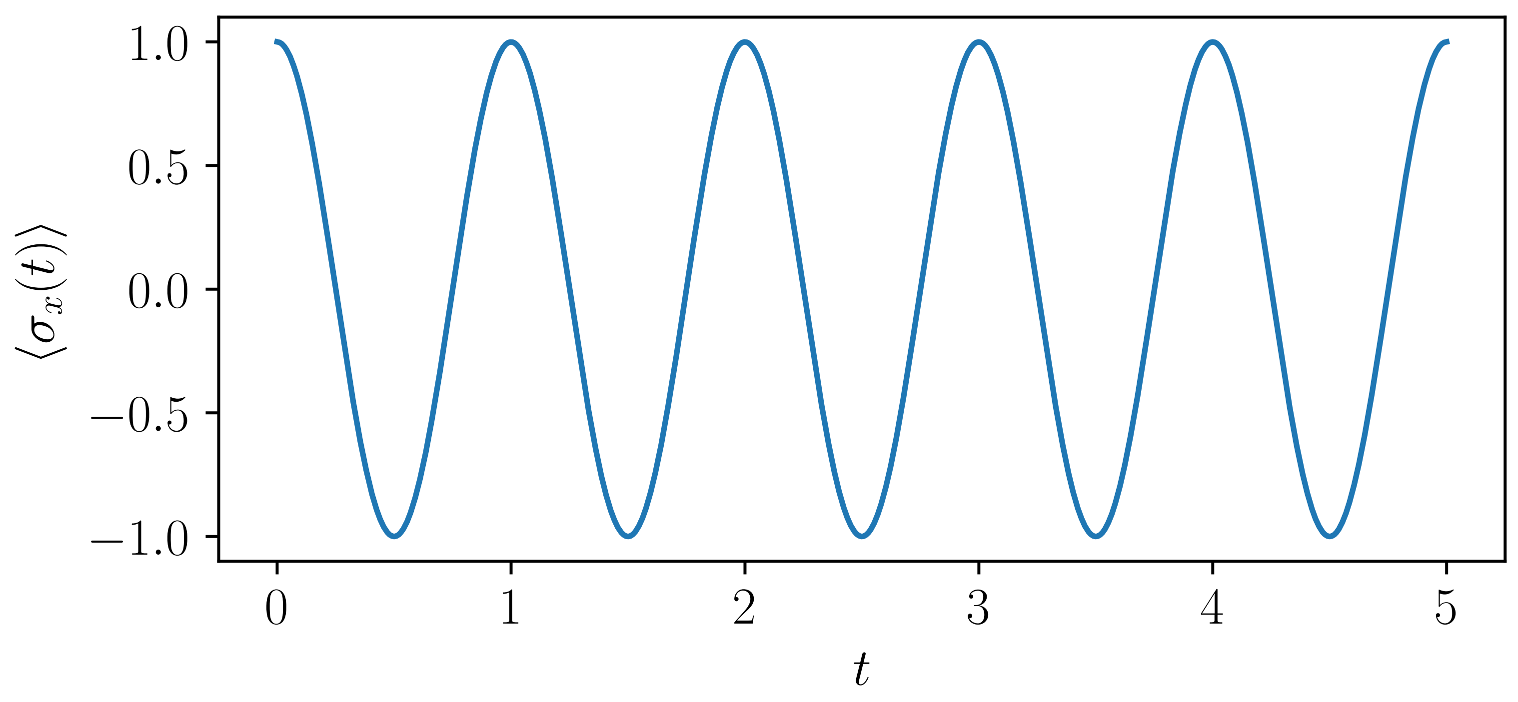

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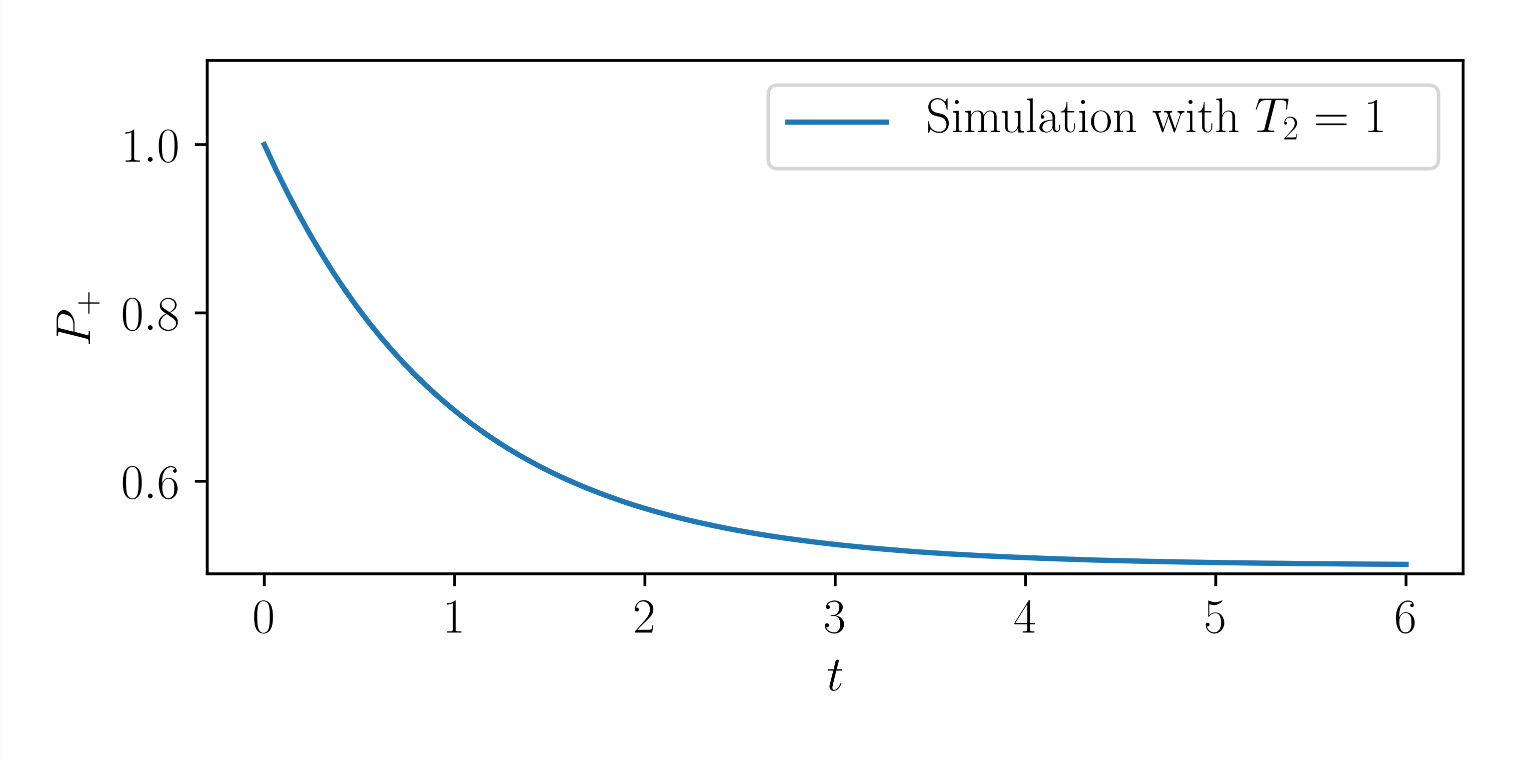

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] + \sum_i \gamma_i \left(L_i \rho L_i^\dagger - \frac{1}{2}\left\{ L_i L_i^\dagger, \rho \right\} \right)$$